Academy Journal of Science and Engineering
Available online @ www.academyjsekad.edu.ng
AJSE 15(1) 2021
Original Research

Experimental Investigation of the Relationship between the Compressive and Flexural Strengths of Concrete made with Sisal Fibre and *Bacillus Coagulans*

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Abstract

This paper is an experimental investigation of the effects of combining sisal fibre reinforcement with *Bacillus coagulans* bacteria on the compressive and tensile strengths of concrete. It was aimed at determining the relationship between the compressive strength and flexural tensile strength of such concrete. A normal concrete mix of 1:1.5:2 with water cement ratio of 0.5 was reinforced with Sisal fibres in the range of 0.5-1.25% in step 0.25% by weight of the dry constituent of the mix and then mixed with the bacteria solution at $12x10^8$ cell/m density. Concrete cubes and beam specimens were tested at 28days and the result indicated that up to the amount of fibre reinforcement tested, both the compressive and tensile strengths were higher than that of the control mix for all mixes. Highest strengths were obtained at 1.25% fibre addition with medium workability without admixture. Mixes with fibre reinforcement combined with bacteria were stronger in compression compared with corresponding mixes with only fibre reinforcement. However, mixes with fibre reinforcement combined with bacteria were weaker in tension compared with corresponding mixes with only fibre reinforcement. The relationship between flexural strength and compressive strengths of the mixes remained fairly constant across the level of fibre reinforcement tested; for only sisal reinforcement this was about 14%. However, for fibre reinforcement combined with bacteria treatment this was about 12%.

Key Words: *Bacillus Coagulans*, Compressive Strength, Concrete, Flexural Strength, Sisal fibre, Microbial Induced Calcite Precipitate

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1. INTRODUCTION

Two of the processes for improving the quality of normal concrete are Microbiology Induced Calcite Precipitate (MICP) and Fibre reinforcement. MICP is a recent development (Jing and Xianzhi, 2018) and is a process in which appropriate micro organisms such as bacteria are introduced into concrete or soils for construction either at the mixing stage or into the curing liquid, The bacteria in the presence of a precipitating agent produces Calcium Carbonate ($CaCo_3$) which is precipitated to fill the pores and micro-cracks that are normally present in normal concrete or compacted soils (Claisse et al, 1997, Khan, 2003, Ramakrishnan et al, 2014). By filling these pores and cracks, the concrete or soil becomes denser and stronger leading to higher strength and durability as have been proven by many researches (Akash et al, 2019, Rahat and Navneet, 2011, Puranik et al, (2019)). Karanja et al. (2019) reported that several research studies have indicated that the MICP process result in increase in compressive strength of between 9% and 25%. However, observed strength increase or sometimes negative results were dependent on the species of bacteria, the concentration of the bacteria and the method of application (Akash et al, 2019, Karanja et al, 2019, Kunaminemi & Meena, 2017). Also many researcher works have shown that application of MICP led to improvement of durability of the concrete (Chahal et al, 2012). While much work has been done on the compressive strength and durability of bacteria concrete, there have been few reported works on the effect on the tensile strength.

The advantages of introduction of fibre in brittle matrix have been known from ancient time with the introduction of straw and vegetable fibres into the molding of soil and clay bricks for construction. In recent times, the technology has been introduced into concrete production and development is ongoing all over the world (ACI Committee 544:1974 & 2010). The introduction of small length fibres dispersed into concrete in the mixing stage has been shown to improve not only the strength of the concrete but most especially the cracking behaviour. The dispersed fibres tend to bridge the tensile cracks that usually form after the tensile strength of the concrete has been overcome and can lead to a more ductile post cracking behaviour. The resistance to crack opening provided by the fibres leads to delay in crack propagation and eventual failure which ultimately leads to higher failure load even if the cracking load is not affected (Bentur and

Mindess, 1990; Grija et al, 2016; Romauldi and Batson, 1963;).

Many types of fibres are available and have been researched and explored successfully in fibre reinforced concrete, these include in broad categorization industrial and natural fibres. Industrial fibres include metallic fibres, the most popular and effective of which is steel fibres and polymer fibres, the most popular of which is polypropylene (ACI Committee 544b). Natural fibres that have been explored include, but not limited to coir/coconut, Sisal, Jute, Hibiscus cannabinus, flax, cotton, bamboo, banana and aloe vera (Yaseen et al, 2019; Majid Ali, 2012, Manonmani, et al, 2019; Kavitha and Kala, 2017). The strongest/toughest and the natural fibres and ones with the best prospect are coconut and sisal fibres. Though less effective due to lower strength and durability considerations, natural fibres have the better prospect in developing countries, especially in tropical regions of the world where these are easily grown. Natural fibres do not undergo complex industrial processes and they are more economical, are readily available and eco-friendly. Sometimes, natural fibres are available as wastes or agricultural by-products making them cheap and affordable for construction purposes.

Though the two processes individually have been reported to enhance the quality and strength of concrete, this study aims to explore the effect of combining both processes to evaluate the effect of the combination on the strength properties of concrete and to determine the relationship between the compressive strength and the tensile strength of concrete so treated. In this study, Sisal fibre which is readily available in Nigeria has been combined with *Bacillus Coagulans*, a soil bacteria which has been successfully utilised for MICP and found to improve the strength and durability of concrete (Oriola et al, 2018).

2. MATERIAL AND METHODS

2.1 Materials

The following materials with the stated quality and properties were utilised in this study

a) Cement

The cement used was the Dangote's 3X brand of Portland-Limestone Cement of Grade 42.5N conforming to the relevant Nigeria Standard for cement (NIS 444-1:2003) and was sourced from local market in Kaduna.

b) Fine Aggregate

Natural river sand was obtained from Local Suppliers at the Mando Tipper

Garage, Kaduna. Preliminary tests indicate that it has a specific gravity of 2.7 and is well graded, falling within the acceptable limit for concrete work according to BS 882. The particle size distribution as obtained from Sieve analysis is as presented in Fig 1. The sand falls largely within the limit for medium coarse sand as per BS 882.

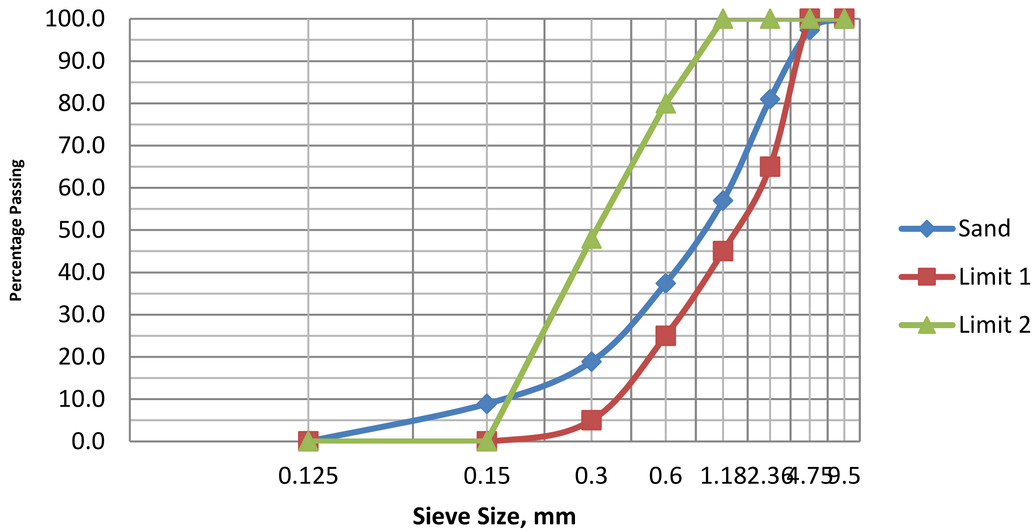

Fig 1: Particle Size distribution of fine aggregate

(c) Coarse Aggregate

The Coarse aggregate used for the experiment was obtained from Local Suppliers at Mando Roundabout, Kaduna. It is 20mm maximum size machine crushed granite chippings with particle size distribution obtained from Sieve Analysis as presented in Fig 2. From Fig 2, the coarse aggregate can be classified as single sized 20mm coarse aggregate as per BS 882. The coarse aggregate had a Specific gravity of 2.61.

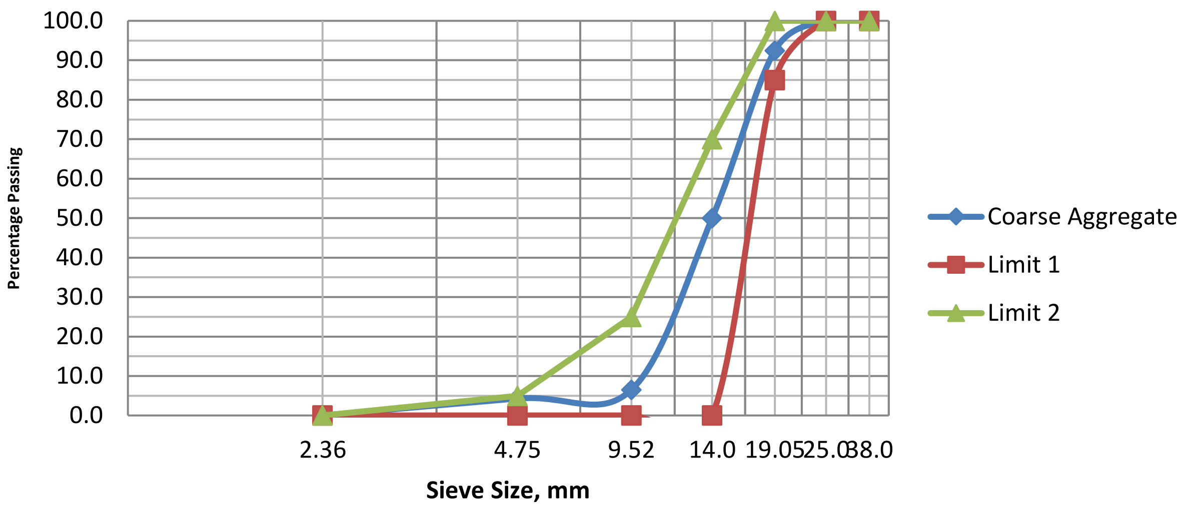

Fig 2: Particle size distribution of coarse aggregate

(d) Water

Water used for mixing and curing was obtained from the Structures Laboratory, Department of Civil Engineering, NDA. It was at ambient temperature of about 25-30°C and portable, therefore suitable for concrete work.

(e) Bacteria

Experimental results from previous work done in the Department of Civil Engineering NDA, Kaduna (Oriola et al, 2018), has indicated that of the available bacteria for the work, *Bacillus coagulans* at density of $12x10^8$cell/ml (determined using the McFarland Turbidity scale) performed better in terms of strength and durability of concrete. Therefore, *Bacillus coagulans* solution at this density was therefore chosen for the study.

e) Sisal Fibres

The Sisal fibres used in the study was obtained from local Supplier in Kaduna Central Market and cut into 40mmm lengths; this is at an aspect ratio of about 300. The properties of the fibres as determined are presented in Table 1.

Table 1: Properties of Sisal fibre

Property	Unit	Quantity
Natural humidity	%	14.48
Average diameter	mm	0.13
Specific gravity	g/cm^3	0.22
Tensile Strength for One strand	N/mm^2	10.60
Colour	Shiny white	-

2.2 Methods

a) Mix Design

A normal concrete mix (control) was designed to produce a concrete of grade 40 (f_{cu} = $40N/mm^2$). The mix adopted was 1:1.5:2 with a water-cement ratio of 0.5. Water-cement ratio 0f 0.5 was chosen to ensure that the workability of the concrete mixes with fibre addition were within medium to high workability range (50mm-100mm slump) without the use of workability agent. Two sets of mixes were produced as follows:

i) **Sisal Fibre Reinforced Concrete**: To the control mix was added Sisal fibres. Sisal fibre addition was at 0% 0.5%, 0.75%, 1.0%, 1.25% and 1.5% by weight of dry constituent of mix.

ii) **Microbial Treated Sisal Fibre Reinforced Concrete**: To the Sisal fibre reinforced mixes were added solution of *Bacillus coagulans* at $12x10^8$cell/ml density.

b) Mixing and Casting

All mixing was by hand and with water as per the control. However, for the microbial treated concrete, 400ml of *B. coagulans* solution which represent about 25% of the mixing water was used to replace equal volume of water for each mix, in order not to alter the water-cement ratio of the mix. Mixing was on a steel plate until a uniform consistency was obtained. Casting was in three layers in 3 cube gang wooden moulds (See Fig. 3) and compaction was on a Flat Vibrating Table in the Civil Engineering Laboratory of the Nigerian Defence Academy, Kaduna. For each mix, six (6) 100mm cubes were cast to determine the compressive strength. Likewise, three (3) 100mm x 100mm x 500mm beams were cast to determine the flexural tensile strength.

Fig. 3: Casting of Concrete Cubes for Compressive Strength

(c) Curing

The cubes were de-molded and cured in ordinary water at ambient temperature.

2.3 Tests

a) Workability

The workability of the concrete mixes was evaluated with the Slump test according to BS EN 12350-2:2009

b) Compressive Strength Test

Crushing of concrete cubes samples was carried out to determine the compressive strength of the sisal fibre reinforced concrete according to BS EN 12390 Part 3. The test was conducted in the Civil Engineering Laboratory of NDA, using the ADR 2000BS analogue Type Compression Testing Machine (See Fig. 4).

c) Flexural Tensile Strength Test

The flexural tensile strength of the concrete beams was determined in the laboratory of the Department of Civil Engineering, Kaduna Polytechnic, Kaduna. The test was carried out using the 3-point loading set up at a span of 400mm (See Fig 4). The test was carried out in accordance with BS EN 12390 Part 5.

Fig 4: Compressive & Flexural Tensile Strength Tests Set Up

3.0 RESULTS AND DISCUSSION

a) Workability

The results of the workability using the Slump test is presented in Table 2. All mixes exhibited true slump as shown in Fig 5.

Table 2: Slump of Concrete Mixes (SFRC & SFRBC)

% Fibre	Slump (mm)
0	110
0.5	75
0.75	65
1.0	60
1.25	50
1.5%	40

The workability of the SFRC mixes was not significantly different from those of SFRBC of similar fibre content, so the result has been presented as one here. This is expected because the mixing liquid content was maintained by substitution of water with the same volume of bacteria solution. The workability of the concrete was within the medium to high workability range (Wikipedia) except for that of 1.5%. Therefore, further work was discontinued on 1.5% fibre addition.

Fig. 5: Slump of Mixes with different Fibre Content

b.) Compressive Strength Properties

The results of the compressive strength test are presented in Fig 6.

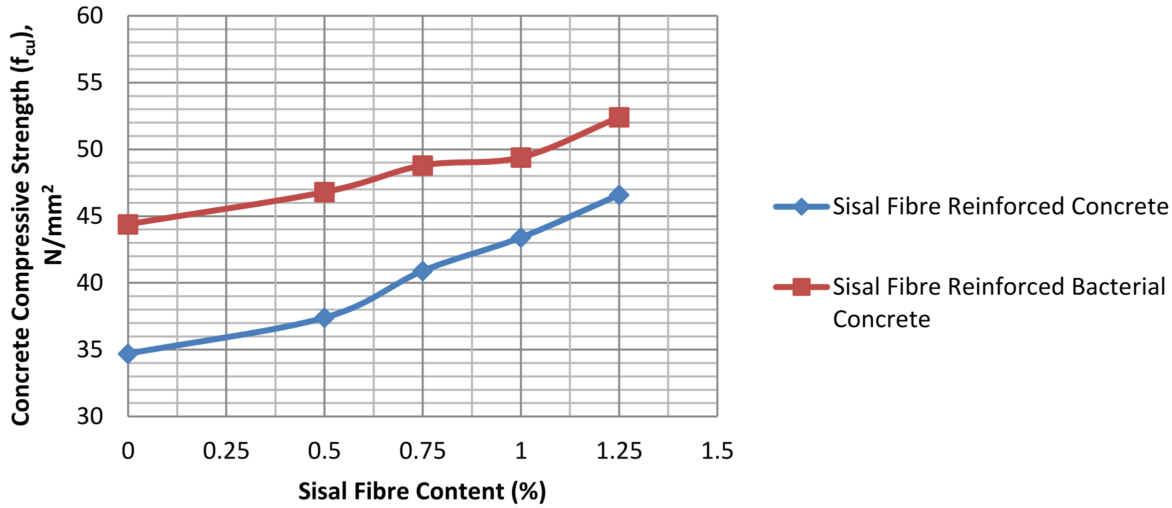

Fig. 6: Variation of Compressive Strength with Different Fibre Content for the Different Types of Concrete

As may be observed from Figure 5, the target grade of 40N/mm^2 was not achieved with the normal concrete (control) but was achieved at 0.75% fibre content for Sisal Fibre Reinforced Concrete. However, the target was achieved at 0% fibre content with Sisal fibre Reinforced Bacterial Concrete. The SFRBC was consistently stronger than its counterpart without bacteria addition. This may be as a result of the bacteria producing precipitates which filled up the pores in the concrete thereby increasing the compressive strength. The average improvement in compressive strength of SFRBC over that of SFRC ranged between 28% and 12% for different percentages of sisal fibre as presented in Table 3. However, the increase in strength is higher at lower fibre content. This may be due to the fact that more fibre leads to possible pockets of pores around clumps of fibres which may not be completely filled by the $CaCo_3$ precipitates, as postulated by Claisse et al; 1997 and Khan, 2003. In this study, the application of only MICP treatment increased the compressive strength of the concrete by 28%, this is comparable with the highest value obtained by previous researchers (Karanja et al, 2019). Furthermore, an addition of 1.25% of Sisal fibre increased the compressive strength by 34.3% and this improvement was increased to 51% when the fibre reinforcement was combined with the MICP treatment.

Table 3: Comparison of the Compressive Strengths of SFRC and SFRBC

Sisal Fibre Content (%)	Compressive Strength of SFRC (N/mm^2)	Compressive Strength of SFRBC (N/mm^2)	Ratio of Strength
0.0	**34.7**	**44.4**	1.28
0.5	**37.4**	**46.8**	1.25
0.75	**40.9**	**48.8**	1.19
1.0	**43.4**	**49.4**	1.14
1.25	**46.6**	**52.4**	1.12

b) Flexural Tensile Strength Properties

The results of the flexural tensile strength test are presented in Fig 7. The experimental values have been reviewed down by 13% because according to BS EN 12390 Part 5 extensive studies have indicated that 3 point flexural test results were consistent about 13% higher than 4 point flexural test set up results.

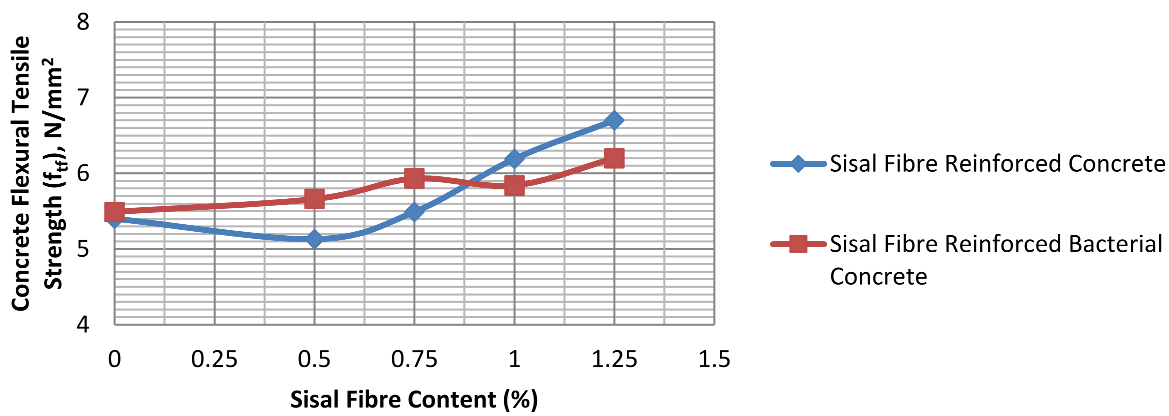

Fig 7: Flexural Tensile Strengths of Different types of Concrete at various Sisal Fibre Content

Figure 7 reveals that the flexural strengths of both SFRC and SFRBC increased with increasing fibre content. The flexural tensile strengths were generally higher than that of normal concrete at all fibre content. Furthermore, the tensile strength of SFRBC was higher than that of SFRC at lower Sisal fibre content (≤ 0.75%) but surprisingly lower at higher fibre content (>0.75%). In this study the highest improvement in tensile strength was achieved at 1.25% fibre content. With fibre reinforcement only the improvement was of the order of 24.5% but when combined with bacteria, it was only 14.8%. It implies that the improvement in tensile strength is not comparable to that achieved with the compressive strength.

c) Relationship between the Compressive Strength and Flexural Tensile Strength

The relationship between the compressive strength and the flexural strength for the different types of concrete at different fibre content is as presented in Tables 4 and 5.

Table 4: Flexural Strength to Compressive Strength Ratio of SFRC

Mix ID	Sisal Fibre Content (%)	Compressive Strength (N/mm^2)	Flexural Strength (N/mm^2)	Flexural Strength /Compressive Strength (%)
SFRC1	0.0	**34.7**	**5.4**	15.6
SFRC2	0.5	**37.4**	**5.13**	13.7
SFRC3	0.75	**40.9**	**5.49**	13.4
SFRC4	1.0	**43.4**	**6.19**	14.3
SFRC5	1.25	**46.6**	**6.7**	14.3

From the result in Table 4, the percentage ratio of the tensile strength to the compressive strength of SFRC did not vary significantly; it has an average of 13.9% across the content of Sisal fibre (0.5% - 1.25%). However, the value for the control (0% Sisal fibre content) was surprisingly higher at 15.6%.

Table 5: Flexural Strength to Compressive Strength Ratio of SFRBC

Mix ID	Sisal Fibre Content (%)	Compressive Strength (N/mm^2)	Flexural Strength (N/mm^2)	Flexural Strength /Compressive Strength (%)
SFRBC1	0.0	**44.4**	**5.49**	12.4
SFRBC2	0.5	**46.8**	**5.66**	12.1
SFRBC3	0.75	**48.8**	**5.93**	12.2
SFRBC4	1.0	**49.4**	**5.84**	11.8
SFRBC5	1.25	**52.4**	**6.20**	11.8

Table 5 also reveals that the relationship between the flexural tensile strength and the compressive strength of SFRBC is fairly consistent at different Sisal fibre content, the tensile strength is on the average about 11.98 percent of the compressive strength across all fibre content (0.5%-1.25%). This value is surprisingly lower than that of ordinary Sisal fibre reinforced concrete. Again the concrete with no sisal fibre had the highest ratio of flexural strength to compressive strength at 12.4%. Thus, fibre reinforcement has more significant effect on the tensile strength of concrete than microbial treatment.

c) Relationship between Flexural and Compressive Strengths

Researches have indicated that the flexural strength of normal concrete is of the order of 10-14% of the compressive strength (Neville, 2011). Values (about 12-14%) observed in this study are within this range, though closer to the upper limit of observations for normal concrete. Therefore, though sisal fibre, bacteria treatment and combination of sisal fibre reinforcement with MICP (using Bacillus coagulans) increases both the compressive and tensile strengths of normal concrete, the relationship between the flexural strength and compressive strength of concrete for similar compressive strength is not significantly affected. This could generally be explained by the fact that the precipitate acting to fill the pores may not be stronger in tension as the mortar.

In order to compare the observed values with established empirical formulas, the results have been compared with two international codes commonly used in Nigeria, the UK Code (BS 8110) and the European Code (EC2). The Code formulas are from BS 8110 and Eurocode 2 are presented as equations 1&2 and have been compared with the results in Table

$$f_{tf} = 0.63(f_{cu})^{\frac{1}{2}} \qquad (1)$$

$$f_{tf} = 0.45(f_c)^{\frac{2}{3}} \approx 0.39(f_{cu})^{\frac{2}{3}} \qquad (2)$$

Where:

Equation 2 is from details contained in Section 3.1.8 and Table 3.1 of EC2

f_{tf} = Flexural Tensile Strength

f_c = Cylinder Compressive Strength at 28days

f_{cu} = Cube Compressive Strength at 28 days

Table 6: Experiments versus Predicted values for the Relationship Between Flexural and Compressive Strengths

Mix ID	Experimemtal (N/mm^2)		Predicted Flexural Strength (N/mm^2)		Experiment/Predicted	
	f_{cu}	f_{tf}	BS 8110	EC2	BS8110	EC2
SFRC1	34.7	5.40	3.71	4.15	1.46	1.30
SFRC2	37.4	5.13	3.85	4.37	1.33	1.17
SFRC3	40.9	5.49	3.98	4.64	1.38	1.18
SFRC4	43.4	6.19	4.14	4.82	1.50	1.28
SFRC5	46.6	6.70	4.30	5.65	1.56	1.19
SFRBC1	44.4	5.49	4.20	4.90	1.31	1.12
SFRBC2	46.8	5.66	4.31	5.07	1.31	1.12
SFRBC3	48.8	5.93	4.40	5.21	1.35	1.14
SFRBC4	49.4	5.84	4.43	5.26	1.32	1.11
SFRBC5	52.4	6.20	4.56	5.47	1.36	1.13

From Table 6, the two formulas from BS 8110 and EC2 underestimate the flexural strength of the two types of concrete, though the EC2 formula gave closer values. This is expected because Code formulas are normally conservative and could be considered lower bounds to make allowance for safety. From the study result, the EC2 form could be adopted for calculating or determining the flexural strength of the different type of concrete from the compressive strength.

For only Sisal fibre reinforcement and within the range of fibre percentage addition considered:

$$f_{tf} = 0.39(f_{cu})^{\frac{2}{3}} \quad (3)$$

Note that Equation 3 does not have any term for the amount of fibre content, this is because, it was observed that though the fibre content affected the magnitude of the two strengths, it appears did not affect the relationship between them significantly.

4. CONLUSION AND RECOMMENDATIONS

From this experimental study the following conclusion may be reached:

a) Sisal fibre reinforcement of up to 1.25% by weight of dry constituent of concrete mix is possible without workability agent.

b) Compressive and tensile strengths of concrete mixes increased with increasing fibre addition up to 1.25% addition but not at the same proportion.

c) MICP treatment with *Bacillus coagulans* cause further increase in both compressive and tensile strengths.

d) The relationship between the flexural strength and compressive strength of concrete remained fairly constant at all percentage of fibre addition tested with or without bacteria treatment.

e) For all level of fibre addition the ratio of flexural strength to compressive strength of concrete mixes was about 14% for sisal fibre only and about 12% for sisal fibre with bacterial treatment.

The following recommendations can be made:

a) For mixes with medium workability without workability agent, sisal fibre reinforcement up to 1.25% addition of dry constituent of mix may be adopted for maximum benefit.

b) The flexural strength of concrete mix with sisal fibre reinforcement only or with sisal fibre reinforcement combined with *Bacillus coagulans* bacteria treatment at 12x 108 cell/ml and 25% of mixing water substitution by bacteria solution may be taken as 12% of compressive strength or conservatively calculated with $f_{tf} = 0.39(f_{cu})^{2/3}$.

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